Application of the *ACRUSalinity* daily agrohydrological model to the Winter Rainfall region of South Africa

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Abstract

ACRUSalinity is a newly developed salinity module of the ACRU daily catchment model. It enables the modelling of salt generation within catchments, taking into account effects of the spatial distribution of rainfall, geology and farming practices, on salt yields.

In a current study, the ACRUSalinity model is being applied to the Berg River Catchment to investigate the effects of impounding runoff from mountainous regions on the salinity levels downstream. TDS sampling in the lower reaches of the river revealed that, contrary to expectation, the highest TDS values occurred during the winter rainfall season. This could be attributed to the dryland agriculture, the release of salts from weathered Shale and the mobilisation of salts when sufficient transport capacity is available during the rainy season.

Preliminary outputs from the model indicate that the high TDS concentrations during the winter months could be simulated and that the observed seasonal TDS patterns were be preserved.

Keywords: *salinity, modelling, daily, South Africa, river impoundment.*

1 Introduction

Daily hydrosalinity modelling was used in this study to quantify the potential impacts of the Berg River Dam (South Africa) on downstream water quality. The Berg River mainstem is approximately 270 km long and drains an area of 9000 km2. The headwaters begin in the Franschoek and Jonkershoek mountains (upstream of the G1H020 gauge), flowing in a general north-westerly direction towards the estuary, downstream of Misverstand Dam, which is gauged by G1R003 (Figure 1.1). The catchment falls within the winter rainfall region of South Africa with perennial tributaries on the eastern mountainous side and semi-perennial tributaries on the flatter western side. The geology consists primarily of Malmesbury Shale, with Table Mountain Sandstone (TMS) overlying the Shale in the upper reaches of Paarl. Water from the catchment is used for irrigation (particularly in the upstream areas), domestic purposes, livestock, recreation and maintenance of the aquatic ecosystem (Department of Water Affairs and Forestry (DWAF), 1993a).

Before construction of the Berg Water Project (BRP), concerns were raised about the impacts of the Dam on concentrations of Total Dissolved Solids (TDS) in the lower Berg River. In the Western Cape System Analysis (WCSA) an assessment was made of water quality in the Berg River prior to construction of the Dam (DWAF, 1993a). It was found that TDS concentrations increased downstream due to the geology of the area. Tributaries draining the upper reaches of the Catchment had very low TDS concentrations when compared to tributaries draining the Shale dominated areas downstream of gauging station G1H013. The estuary at the river mouth was slightly saline in summer due to intrusion of sea water, while the winter flows served to flush the saline water from the estuary. Thus, the catchment appeared to be in balance with respect to TDS concentration, where good quality water upstream diluted saline water downstream.

The WCSA (DWAF, 1993a) included an estimation of potential impacts of the BRP using the monthly FLOSAL hydrosalinity model. It was found in the study that impoundment of good quality water upstream is likely to cause a marginal deterioration in the water quality at Misverstand Dam. It was, however, recommended that a detailed study be done prior to any major developments in the catchment.

In a follow-up study, salinity parameters were updated and the FLOSAL model showed that the BRP would increase average TDS concentrations at Misverstand Dam by an order of approximately 50-60 mg/l. Figure 1.2 depicts the exceedence curves for present day TDS conditions and predicted TDS conditions after construction of the BRP. Contrary to expectation, the highest TDS concentrations occurred during the winter months and this was attributed to the dryland agriculture, release of salts from weathered Shale and the mobilisation of salts when sufficient transport capacity is available during the rainy season. As singular hydrological events were not depicted with the monthly FLOSAL modelling, it was recommended that the *ACRUSalinity* daily model be used for the Berg River Catchment (BRC) (DWAF, 2004).

The primary objective of this study was to quantify the potential impacts of the Berg River Dam on TDS concentrations downstream, using *ACRUSalinity*. The model provided a daily time series of flow and concentrations of the tributaries discharging into the Berg River main stem. The following tasks were required:

- Configuration of the model including delineation of the catchment
- Data acquisition and preparation using preprocessors
- Verification of the model for flow-related parameters
- Verification of the model for salinity-related parameters

Figure 1.1. A map of the Berg River Catchment from its upper reaches to Misverstand Dam.

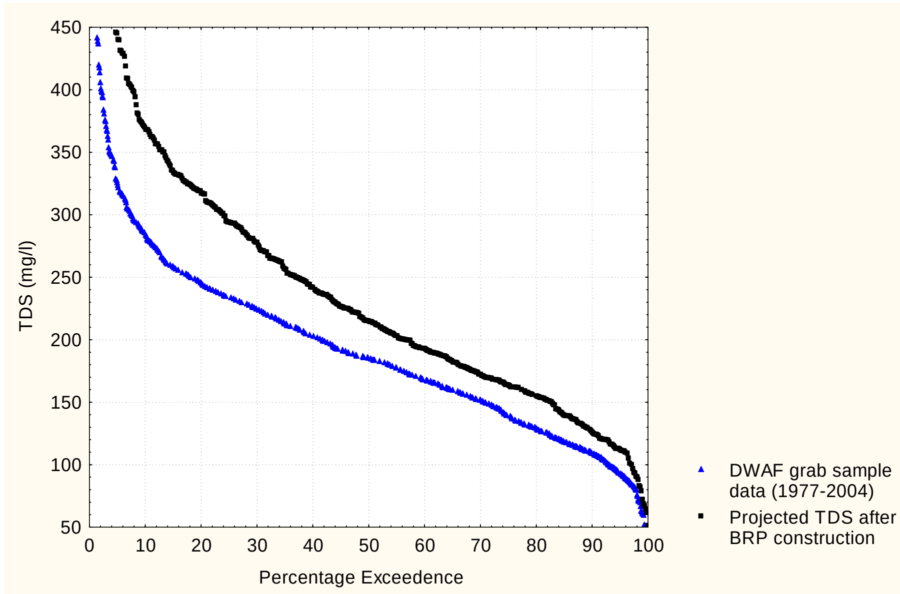

Figure 1.2. TDS Exceedence curves for present day conditions (G1R003) and projected conditions at Misverstand Dam after construction of the Berg River Project

2 Application of ACRU*Salinity* to the Berg River Catchment

2.1 Module description

ACRU*Salinity* is the hydrosalinity module of the daily agrohydrological model ACRU2000. The latter is a catchment scale model that can be used for small (lumped) or large (distributed) catchments. The original ACRU model was developed by the Department of Agricultural Engineering, University of Natal in Pietermaritzburg in 1975. ACRU2000 is programmed in Java language and enables a multi-layered soil water budget to be determined for a catchment. The model requires daily rainfall and evaporation data and simulates the impacts of land-use and climate change on a hydrological system (Teweldebrhan et. al., 2003).

2.1.1 Module concepts

Salt is input via rainfall and irrigation water onto the top soil horizon of a catchment. Water either moves up or down the soil profile depending on the level of drainage and saturation. The *ACRUSalinity* module, however, does not account for water and solute flux in unsaturated soil.

Salt generation in soil and ground water follows first-order rate kinetics while quickflow is enriched with salt from the topsoil horizon due to upward movement of water to meet evaporative demand. The model, however, does not account for salt enrichment of stormflow due to surface salt crusts, flow near the surface or urban effluent. This component of flow is therefore assumed to have the same level of salinity as the average salinity of the rainfall.

The salt balance is determined through instantaneous mixing of surface and subsurface flows and solutes are transported by advection. Reservoir salt balances assume complete mixing within the time-step and advection is described by a two-cell plug-flow model.

2.2 Configuration of the ACRU model for the Berg River catchment

The application of the ACRU hydrological model to a developed catchment such as the Berg River is a challenging task. Several factors contribute to this level of complexity. These include (1) the presence of many farm dams, (2) the varying abstraction rates of irrigation water from these farm dams, (3) variation in Mean Annual Precipitation (MAP) throughout the catchment and (4) the spatial distribution of crops (irrigated and dry-land) within the catchments. The approach employed to overcome these obstacles in the study is discussed below.

2.2.1 Delineation of the Berg River catchment

To facilitate the process of catchment delineation it was decided that two sets of primary sub-catchments should be defined and that these should correspond to watershed boundaries and farm dam boundaries, as defined in the WCSA (DWAF, 1993a). In the WCSA the boundaries were demarcated at the 1990 level of development and represent the sub-catchment area contributing runoff directly into the "dummy" farm dam. The dummy dam represents the combined capacity of all the farm dams upstream of this boundary.

In this way it was possible to create an exploded menu (i.e. containing pseudo sub-catchments) where artificial nodes were placed at the outlet of each primary catchment boundary.
It should be emphasised that the delineation of sub-catchments had to be structured to provide a time series of flow and concentrations of the tributaries discharging into the Berg River main stem. As an example, the primary sub-catchments between Gauging stations G1H020 and G1h036 is depicted in Figure 2.1 and the ACRU system configuration for that sub-catchment is depicted in Figure 2.2.

2.3 Data preparation for the ACRU model

The major input parameters to ACRU include daily rainfall, farm dam size and location, and land-use data. The ensuing sections present not only the data that was prepared for modelling but also the preprocessor programs that were used for preparation, as well as their availability to the model user.

2.3.1 Rainfall

Selection of most appropriate daily rainfall sequence

The Driver Station Approach selects the driver station based on (i) its proximity to the catchment, (ii) its altitude relative to the catchment's mean altitude, (iii) the length of the record and (iv) the extent of missing data. Where missing data is present in the best driver station, it is replaced with data from the next best driver station. Correction factors[1] are then applied to the rainfall of each month in the driver station so that it is more representative of the daily catchment rainfall.

According to Schulze *et al*. (1995) the advantage of this method is the preservation of the statistical properties of this point rainfall and the fact that it is fairly straightforward to apply. The major disadvantage of the approach, however, is the oversimplification of the daily aerial rainfall distribution. For example, the method would presume that the rainfall experienced at that particular rainfall gauge was experienced throughout the catchment.

For this study the data gathered in the Water Research Commission funded project entitled “The Development of an improved Gridded Database of Annual, Monthly and Daily Rainfall” was used. The data contained in this database was obtained from the South African Weather Services (SAWS), the South African Sugar association, the Agricultural Research Council (ARC) and private individuals (Lynch, 2001). Spatial rainfall information was also available in a shape file (personal communications, Pike A., 2004) and this was used for identifying all the rainfall gauges in the immediate area.

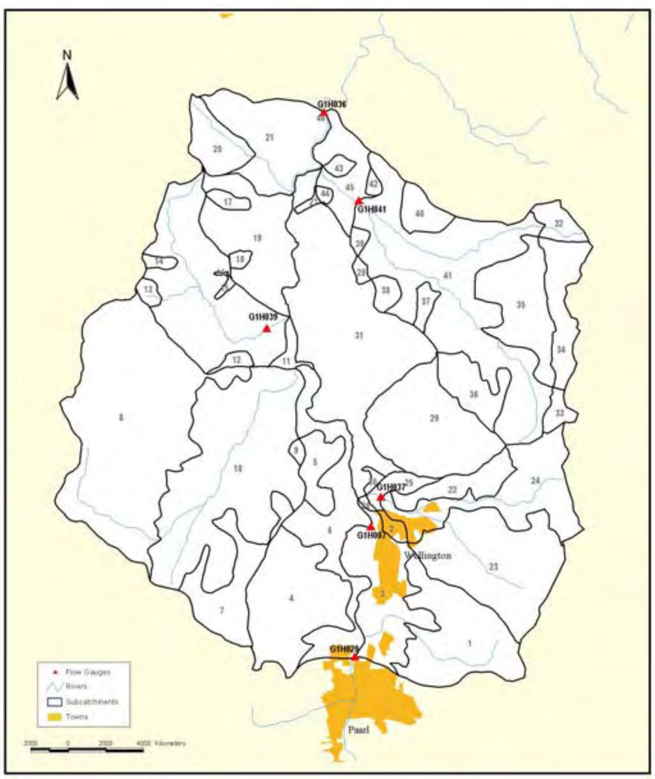

Figure 2.1. Primary sub-catchments defined for the Berg River catchment between gauging stations G1H020 and G1H036

[1] The correction factor for each month is calculated as the ratio of the median monthly precipitation of the driver to median monthly precipitation of the catchment (Schulze, *et al*., 1995)

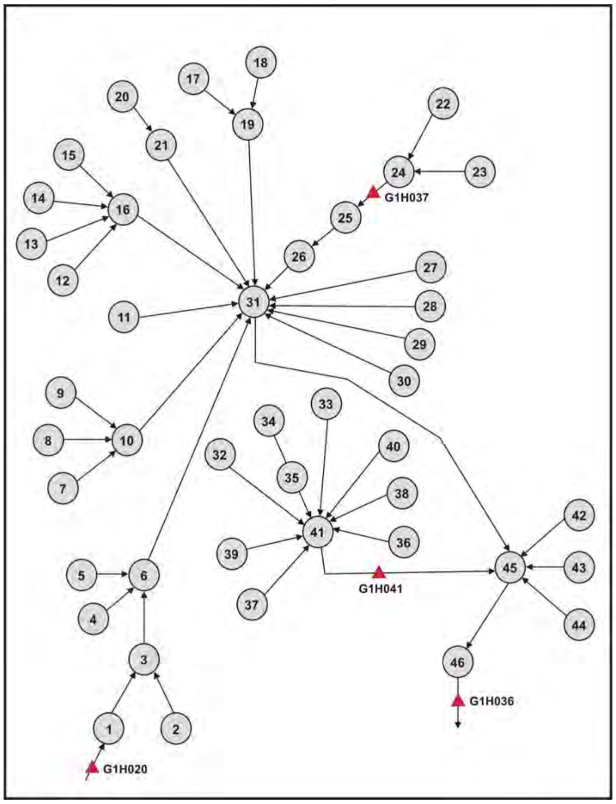

Figure 2.2. ACRU system layout for the Berg River catchment between gauging station G1H020 and G1H036

The preprocessor CALC_PPTCOR (personal communications, Pike A., 2004) was used for prioritizing the rainfall gauges. Selected rainfall files were extracted from the rainfall database using the program BR_SAWB (Lynch, 2001). During the latter stages of this study the procedure for patching daily rainfall data was done using the Daily Rainfall Data Extraction Utility program (Kunz, 2004), which allowed for the extraction of previously patched rainfall data from its database.

CALC_PPTCOR (or Daily Rainfall Data Extraction Utility) was used to perform a manual method of infilling missing data. In this method, missing data in the driver station were replaced with rainfall from the second-most appropriate gauge and adjusted by the ratio of the MAP's between the two stations. With this technique the rainfall sequence is preserved.

2.3.2 Landuse

Landuse for the Berg River catchment upstream of Misverstand Dam (G1R003) was obtained from the VAFS study (DWAF, 1999). In this study a similar approach as the VAFS study was adopted. The GIS coverage of the relevant sub-catchments was intersected with landuse information obtained from the Department of Agriculture to produce further sub-divisions of each primary sub-catchment.

The irrigated areas in the lower Berg River were obtained from the aerial photography commissioned by DWAF in 2001. No aerial photography was available for the most southern portion of the lower Berg River catchment (i.e. the portion covered by topographical maps 3318ad, 3318bc) and landuse for this portion was obtained from LANDSAT satellite imagery from the Council for Scientific and Industrial Research (CSIR). The extent of the dryland crops were obtained from the National Landcover Database Project (NLCDP) with only the new irrigated areas superseding the dryland crops. The remaining areas were then assigned the natural vegetation as indicated in the Acocks coverage. The resulting landuse coverage for the lower Berg River is shown in Figure 2.3**.**

2.3.3 Farm dams

Farm dam information for this study was obtained from two sources:

1. Western Cape System Analysis (WCSA) – Hydrology of the Berg River Basin (DWAF, 1993b) and the
2. Voëlvlei augmentation scheme: Feasibility Study (VAFS) – Hydrology Report (Volume 1) (DWAF, 1999)

The delineation of the sub-catchments required for the ACRU model therefore reflect the actual landuse areas, farm dam capacities and abstractions used in previous studies.

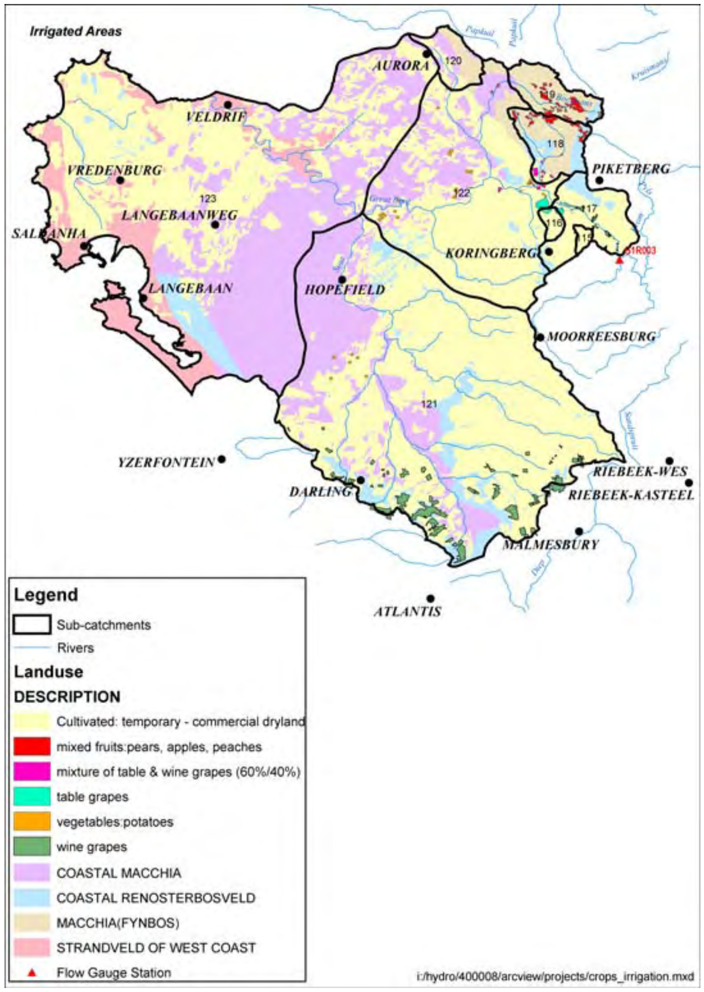

Figure 2.3. Landuse coverage for the lower Berg River catchment

Establishing Farm Dam Boundaries

The demarcation of farm dam boundaries in the WCSA allowed for the determination of capacities using a numerical model and information extracted from the digital terrain data (DWAF, 1993b). The area-capacity relationships of these farm dams were approximated using the relationship shown below:

$$Area = A \times Capacity^{B} \qquad (1)$$

Where, Area is measured in km^2
Capacity is measured in Mm^3

In this study a decision was made to use the most up to date input data available and in the case of farm dams this was the data from the VAFS study (DWAF, 1999), based at the 1996 level of development. A and B coefficients for each calibration sub-catchment as described in equation 1 was obtained from the WCSA report (DWAF, 1999).

The area/volume relationship (equation 1) and the appropriate coefficients are applicable to the single dummy farm dam that was created in that sub-catchment. Since the ACRU setup resulted in the formation of more than one dummy dam it was necessary to develop a ratio that could be used to scale up the combined capacity of the farm dams in the Berg River Catchment between G1H020 and G1H036 such that it matched the capacity quoted in the VAFS study. This procedure allowed for determination of the 1996 capacity of farm dams as reported in the VAFS study for each of the catchments used in the ACRU configuration. Equivalent parameters in ACRU for the A and B parameters are RESCON and RESEXP. These parameters were obtained by plotting volume in m^3 against the surface area in m^2 and then fitting a curve with the form as shown in equation 1.

2.3.3 Salinity

Salinity is represented in this study by TDS concentration, measured in mg/l. Weekly TDS data was obtained from DWAF and where there was only electrical conductivity (EC) measured, TDS was calculated using the site-specific relationship between EC and TDS. The data was then infilled using a **moving-regression** method to produce a daily TDS sequence for use in the model. Simulated values were used to patch missing data, if present after the infilling process (Nitsche, 2000).

3 Verification of the ACRU model

In order to perform a salinity verification it was necessary to do a flow verification first. The flow verification is largely dependent on the rainfall data received from a driver rainfall station and the degree to which that gauge is representative of the catchment rainfall.

3.1 Flow verification at G1H043 (Sandspruit)

The catchment gauged by G1H043 was used as an example as it is characterised by high salinity and would provide a realistic testing of the model's capabilities. Flow verification at this gauge was completed for the period of May 1980 to December 1994 using landuse data obtained at the 1998 level of development. The modelling process did not account for the growth in landuse during the verification period and it was therefore necessary to identify the possible effects of this on the simulated streamflow record. This catchment, however, has a relatively high salinity and it is unlikely that considerable landuse development took place during the verification period. Winter abstraction to fill the farm dams was not modelled and there were no further imports or exports from this section of the river. The record contains a small portion of missing values and these were patched using simulated values.

Overall, the monthly flows were oversimulated as can be seen in Figure 3.1. This could be due to an overestimation of daily rainfall using the "driver rainfall station" approach. Pertinent statistical parameters for the monthly observed and simulated flows at gauging station G1H043 are shown in Table 3.1.

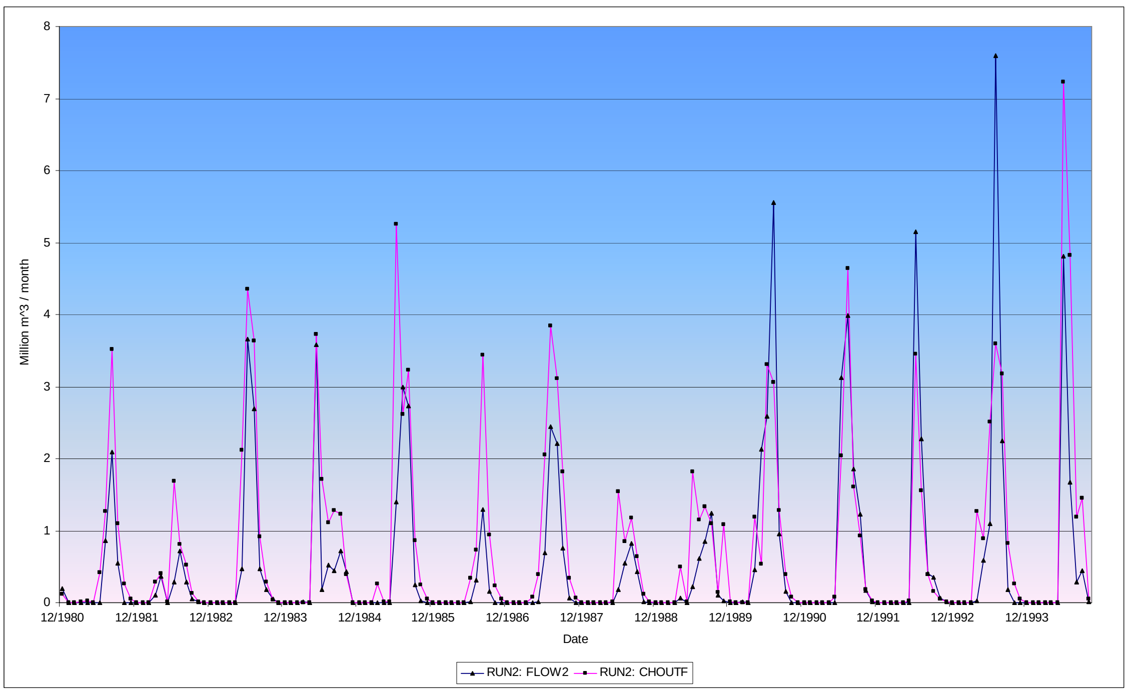

Figure 3.1. Monthly simulated and observed flows at gauging station G1H043

3.2 Salinity verification of the ACRU model

The key statistical parameters involved in the comparison between monthly simulated and observed TDS loads are given in Table 3.2. The statistics imply that the overall difference between simulated and observed loads is small, however, the TDS sequence in Figure 3.2 shows obvious differences between the data sets. There appears to be a 'cancelling out' effect between the oversimulation and undersimulation of TDS loads, which may create the impression that the simulations are representative of observed trends.

Table 3.1. Goodness-of-fit statistics for simulated and observed flows at G1H043

Statistics for G1H043 (1980 –1994)	Monthly totals of daily simulation
Difference between means (%)	-40.79
% difference in standard deviation (-)	-8.91
Coefficient of determination (-)	0.67
Coefficient of efficiency (-)	0.63
Coefficient of agreement (-)	0.89

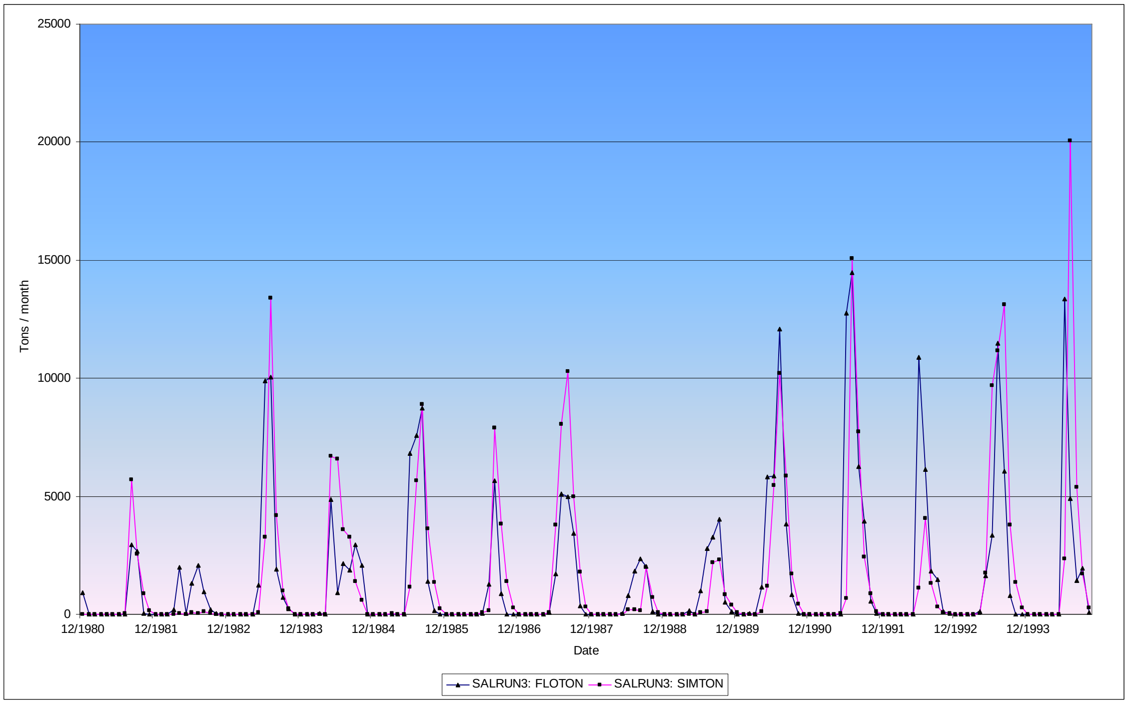

Figure 3.2. Monthly simulated and observed salt loads at G1H043

Table 3.2. Goodness-of-fit statistics for simulated and observed TDS loads at G1H043

Statistics for G1H043 (1980 –1994)	Monthly totals of daily simulation
Average error in flow (mm/day)	26.03
Difference between means (%)	-1.72
Difference in standard deviation (%)	-9.97
Coefficient of determination (-)	0.47
Coefficient of efficiency (-)	0.42
Coefficient of agreement (-)	0.79

In some cases, inaccuracy of the salinity simulations can be attributed to inaccuracies present in the flow verification. In other words, if flow is oversimulated for a particular month, then TDS loads will also be oversimulated for that month on account of excess flow available for transporting salts in the model. Often discrepancies in simulated and observed flow patterns are unavoidable and are often caused by a lack of representative rainfall data.

Nevertheless, observed trends are reflected in the daily simulations, as far as the times when TDS concentrations rise and fall. In the analysis of daily TDS trends, summer months were ignored as these concentrations do not have a considerable effect on the overall TDS loads transported from a catchment. Due to an open ended exponential groundwater algorithm in the model, extremely small streamflows are generated in summer, which attain exaggerated concentrations due to evapo-concentration. Such summer values are obviously artefacts of the model.

Several shortcomings have been identified with respect to the current model capabilities. These surfaced during an on-going feedback process with the model developers and are currently under review and development. The effects can be seen in Figure 3.3 and are as follows:

- There is no interaction between stormflow and the salts on the soil surface and this has led to an over dilution of TDS in the model. This can be seen for G1H043 where daily simulated salinity levels do not reach observed levels at the onset of winter and subsequently drop to well below observed concentrations, in response to increased flow rates.

- *ACRUSalinity* does not simulate the upward movement of water and solutes in unsaturated soils that occurs due to capillary action. This could further reduce the salinity levels being simulated at the onset of a rainfall event.

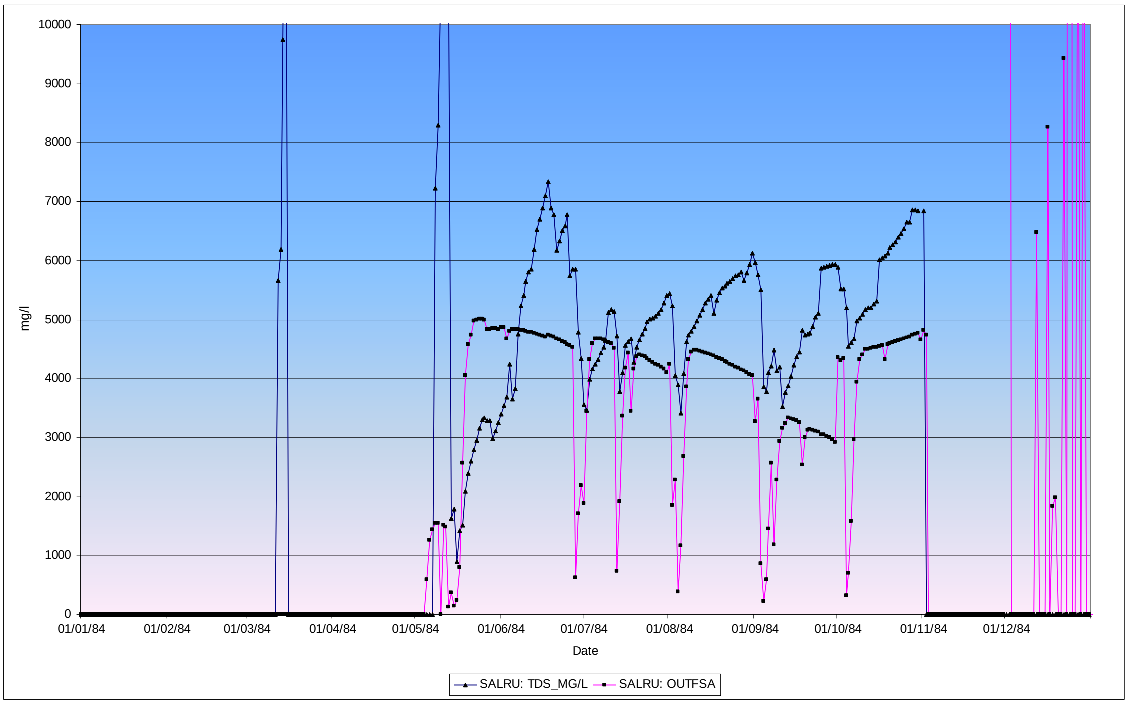

Figure 3.3. Daily simulated and observed salinities at G1H043

4 Conclusions and Recommendations

Simulations modelled with ACRU*Salinity* showed the general salinity trends observed in the lower Berg River Catchment. There were, however, discrepancies regarding the magnitude of salinity levels reached. In the simulations, salinity levels generally dropped lower and rose higher than those observed. Furthermore, salinity levels at the onset of winter were not capable of reaching the observed levels. This effect was attributed mainly to the following short-comings identified in *ACRUSalinity*:

(1) *AcruSalinity* does not simulate the upward movement of water through the soil that occurs due to capillary forces under unsaturated conditions. This has caused an under-estimation of salt loads being transported by run-off.

(2) Secondly, the model does not account for the interaction of stormflow with the salts in a catchment and this has caused a 'dilution effect' associated with stormwater flow. The model therefore simulates a considerable drop in salinity levels during stormflow. These assumptions of the model, however, are unrealistic and becomes more evident in a highly saline catchment such as the lower Berg River where the impacts of stormflow interaction with the salts in a catchment has been observed and high stormflows in winter are responsible for transporting the large salt loads observed.

The aforementioned aspects are currently under review for further development and it is worth mentioning that an on-going feedback process ensued with the model developers, greatly improving the model functionality. Another important aspect of the study is that it is the first application of *ACRUSalinity* to a catchment with known salinity problems, in contrast to the low salinity test catchment in the Upper Mkomazi River, KwaZulu-Natal originally used. This is probably why shortcomings of the model algorithms and code could be illustrated in this study.

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